

# Probing the Astrophysics of Cluster Outskirts

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## ABSTRACT

In galaxy clusters the entropy distribution of the IntraCluster Plasma modulates the latter’s equilibrium within the Dark Matter gravitational wells, as rendered by our Supermodel. We argue the entropy production at the boundary shocks to be reduced or terminated as the accretion rates of DM and intergalactic gas peter out; this behavior is enforced by the slowdown in the outskirts development at late times, when the Dark Energy dominates the cosmology while the outer wings of the initial perturbation drive the growth. In such conditions, we predict the ICP temperature profiles to steepen into the cluster outskirts. The detailed expectations from our simple formalism agree with the X-ray data concerning five clusters whose temperature profiles have been recently measured out to the virial radius. We predict steep temperature declines to prevail in clusters at low  $z$ , tempered only by rich environs including adjacent filamentary structures.

**Key words.** galaxies: clusters: general — galaxies: clusters: individual (Abell 1795, PKS 0745-191, Abell 2204, Abell 1413, Abell 1689) — X-rays: galaxies: clusters — methods: analytical.

## 1. Introduction

Galaxy clusters constitute the largest bound structures in the Universe, with their masses up to  $M \sim 10^{15} M_{\odot}$  and outskirts extending out to sizes  $R \sim$  a few Mpcs. These set the *interface* between the intergalactic environment keyed to the cosmology at large, and the confined intracluster plasma (ICP). The latter pervades the clusters at temperatures  $k_B T \propto GM/R \sim 5$  keV and number densities  $n \sim 10^{-3} \text{ cm}^{-3}$ , and so emits copious X-ray powers mainly by thermal Bremsstrahlung (see Sarazin 1988). The ICP coexists with the gravitationally dominant dark matter (DM) component in the baryonic fraction  $m/M$  close to the cosmic value 0.16, and the two build up together from accretion across the cluster boundary.

The build up comprises an early collapse of the cluster body, tailing off into a secular development of the outskirts by smooth accretion and minor mergers (see Zhao et al. 2003; Diemand et al. 2007; Vass et al. 2008; Navarro et al. 2010). In radius, the body ranges out to  $r \sim r_{-2}$  where the slope of the DM density run  $n(r)$  equals  $-2$ ; the adjoining outskirts extend out to the current virial radius  $R$  with steepening density.

In time, the transition is marked by the redshift  $z_t$ ; thereafter  $r_{-2}$  stays put while  $R$  grows larger in a quasi-static, self-gravitating DM equilibrium (described through the Jeans equation, see Lapi & Cavaliere 2009a), to imply for the standard concentration parameter  $c \equiv R/r_{-2}$  observed values  $c \approx 3.5 H(z_t)/H(z_{\text{obs}})$  in terms of the Hubble parameter  $H(z)$ . In the following we adopt the standard flat cosmology (see Dunkley et al. 2009). So values of  $c$  ranging from 3 to 10 correspond for  $z_{\text{obs}} \approx 0 - 0.2$  to *young* or to *old* dynamical cluster ages  $z_t \sim 0.2 - 3$ . The concentration can be directly if laboriously probed with gravitational lensing (see Broadhurst et al. 2008; Lapi & Cavaliere 2009b).

Secular accretion of DM goes along with inflow of intergalactic gas. The ensuing ICP equilibrium is amenable to the

powerful yet simple description provided by the Supermodel<sup>1</sup> (SM; see Cavaliere et al. 2009, hereafter CLFF09).

Clearly, inflows into the cluster outskirts are exposed to the cosmological grip. This is the focus of the present paper.

## 2. Entropy run vs. cluster buildup

The SM expresses in full the hydrostatic equilibrium (HE) of the ICP in terms of DM gravity and of the ‘entropy’  $k \equiv k_B T/n^{2/3}$ . In its basic form, the latter’s *physical* run may be represented as

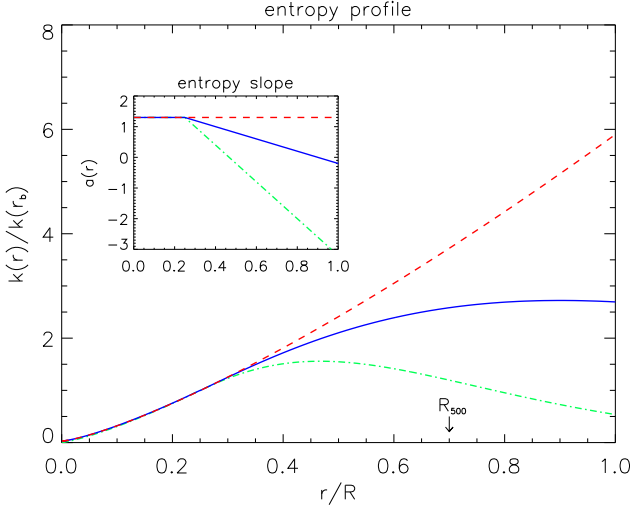
$$k(r) = k_c + (k_R - k_c) (r/R)^a, \quad (1)$$

consistent out to  $r \approx R/2$  with recent analyses of wide cluster samples (Cavagnolo et al. 2009; Pratt et al. 2010). This embodies two *specific* ICP parameters: the central level  $k_c$  and the outer powerlaw slope  $a$ .

The former is set at a basal level  $k_c \sim 10 \text{ keV cm}^2$  by intermittent entropy injections by central AGN feedback (e.g., Cavaliere et al. 2002; Valageas & Silk 1999; Wu et al. 2000; McNamara & Nulsen 2007); the ensuing quasi-stable condition corresponds to cool core morphologies (CC; see Molendi & Pizzolato 2001), featuring a limited central temperature dip and generally large concentrations  $c \approx 6 - 10$ , as discussed by CLFF09.

On the other hand,  $k_c$  may be enhanced up to several  $10^2 \text{ keV cm}^2$  by deep mergers (e.g., McCarthy et al. 2007; Markevitch & Vikhlinin 2007), frequent during the cluster youth; these events give rise to non cool core (NCC) clusters, featuring generally low concentrations  $c \approx 3 - 5$  and a central temperature plateau, scarred in some instances by imprints from recently stalled blastwaves (see discussions by Fusco-Femiano et al. 2009; Rossetti & Molendi 2010).

<sup>1</sup> *IDL* and *FORTTRAN* algorithms which implement the Supermodel and run in a fraction of a second on a standard laptop, can be found at <http://people.sissa.it/~lapi/Supermodel/>.



**Fig. 1.** Examples of entropy profiles (normalized at  $r = r_b$ ) and slopes (inset). Dotted line: after Eq. (1) with  $k_c = 0$  and  $a = 1.3$ . Solid line: Eq. (4) with  $k_c = 0$ ,  $a = 1.3$ ,  $r_b = 0.25 R$ , and  $a' = 0.5$ . Dashed line: Eq. (4) with  $k_c = 0$ ,  $a = 1.3$ ,  $r_b = 0.25 R$ , and  $a' = 1.5$ .

### 2.1. The outer regions

The second term in Eq. (1) describes the powerlaw outward rise expected from the scale-free stratification of the entropy continuously produced by the boundary accretion shock, while the cluster grows larger by slow accretion.

The slope  $a_R$  at  $r \approx R$  with standard values around 1 has been derived by CLFF09 from the shock jumps and the adjoining HE maintained by thermal pressure, to read

$$a_R = 2.37 - 0.47 b_R. \quad (2)$$

Here  $b_R \equiv \mu m_p v_R^2 / k_B T_R$  marks the ratio of the potential to the thermal energy of the ICP (see Lapi et al. 2005; Voit 2005). This reads  $b_R \approx 3 v_R^2 / 2 \Delta \Phi$  when a strong shock efficiently thermalizes into 3 degrees of freedom the infall energy; the latter is expressed in terms of the potential drop  $\Delta \Phi = - \int_{R_{\text{ta}}}^R dr G \delta M / r^2$ , experienced by successive shells of DM and gas that expand; owing to the excess mass  $\delta M$  they turn around at the radius  $R_{\text{ta}} \approx 2 R$  to start their infall toward the shock at  $R$ .

At any given cosmic time  $t$ , Eq. (2) holds at the current virial radius  $R(t)$ . On the other hand, the entropy deposited there is conserved during subsequent compressions of the accreted plasma into the DM gravitational well, while no other major sources or sinks of entropy occur down to the central  $10^2$  kpc. Thus while the cluster outskirts develop out to the current radius  $R(t)$ , the specific entropy stratifies with a running slope  $a(r) = a_{R(t)}$  that retains the sequence of original values set at the times of deposition (see Tozzi & Norman 2001).

Values  $a \approx 1$  obtain on adopting the standard ratio  $R/R_{\text{ta}} \approx 0.5$ , and the simple potential drop  $\Delta \Phi / v_R^2 \approx 1 - (R/R_{\text{ta}}) \approx 0.5$  associated to a flat initial mass perturbation  $\delta M / M \propto M^{-\epsilon}$  with  $\epsilon \sim 1$  that describes the collapse of the cluster *body* as a whole. This implies  $b_R \approx 3$  and  $a \approx 1$  from Eq. (2). In fact,  $\Delta \Phi / v_R^2 \approx 0.57$  obtains from the full DM  $\alpha$ -profile (see CLFF09), implying  $b_R \approx 2.7$  and the standard value  $a \approx 1.1$ .

However, considerable variations of  $a(r)$  are to be expected in the cluster outskirts, as discussed below.

### 2.2. Development of the outskirts

The cluster *outskirts* for  $r > r_{-2}$  originate from the wings of a realistically bell-shaped perturbation, that may be described by  $\delta M / M \propto M^{-\epsilon}$  for  $\epsilon$  exceeding 1 (e.g., Lu et al. 2006). Then the outer potential drop

$$\frac{\Delta \Phi}{v_R^2} = \frac{1 - (R/R_{\text{ta}})^{3\epsilon-2}}{3\epsilon-2} \quad (3)$$

is shallower relative to the body value, so leading to higher values of  $b_R$  and *lower* values of  $a$ . Thus as  $r$  increases outwards we expect  $k(r)$  to deviate downward from a simple powerlaw.

The argument may be phrased in terms of the accretion rate  $\dot{M}$ . A shell  $\delta M$  enclosing the mass  $M$  will collapse when  $\delta M / M$  attains the critical threshold  $1.686 D^{-1}(t)$  in terms of the linear growth factor  $D(t)$  (e.g., Weinberg 2008). So the shape parameter  $\epsilon$  also governs the mass buildup after  $M \propto D^{1/\epsilon} \propto t^{d/\epsilon}$ ; here we have represented the growth factor as  $D(t) \propto t^d$  with  $d$  ranging from  $2/3$  for  $z \gtrsim 1$  to approach  $1/2$  as  $z \rightarrow 0$ . So the outskirts develop from the inside-out, at accretion rates  $\dot{M} / M \approx d/\epsilon t$  that *lower* for  $\epsilon$  exceeding 1, and for  $d$  decreasing toward  $1/2$  at late cosmic times<sup>2</sup>. We add that at small accretion rates the shock position outgrows  $R$  (see Voit et al. 2003), while the shock strength may weaken; both these effects will decrease  $a$  relative to Eqs. (2) and (3), and will be discussed in detail elsewhere.

So we see that *flatter* slopes  $a$  of the entropy are to prevail for *decreasing* accretion rates  $\dot{M}$  of DM and gas; these have a twofold origin. First, the cosmological structure growth slows down at later cosmic times (low  $z_{\text{obs}}$ ), as expressed by  $d < 2/3$ . Second, perturbation wings marked by  $\epsilon > 1$  imply shallow gravitational wells and little available mass to accrete in average environs; the effect may be locally offset (and represented with a smaller effective  $\epsilon$ ) in specifically rich environments, including adjacent filamentary large-scale structures.

The decline of  $a$  from the body value and the entropy bending set in at a radius  $r_b \approx r_{-2}$  where matter began stratifying onto the outskirts just after  $z_t$ . Such a radius is evaluated in terms of the observed concentration in the form  $r_b / R \approx r_{-2} / R \approx 1/c$ , to take on values around  $0.2 - 0.3$  for typical concentrations  $c \approx 6 - 8$  of CC clusters. Hints to this trend loom out in the data by Pratt et al. (2010) and Hoshino et al. (2010).

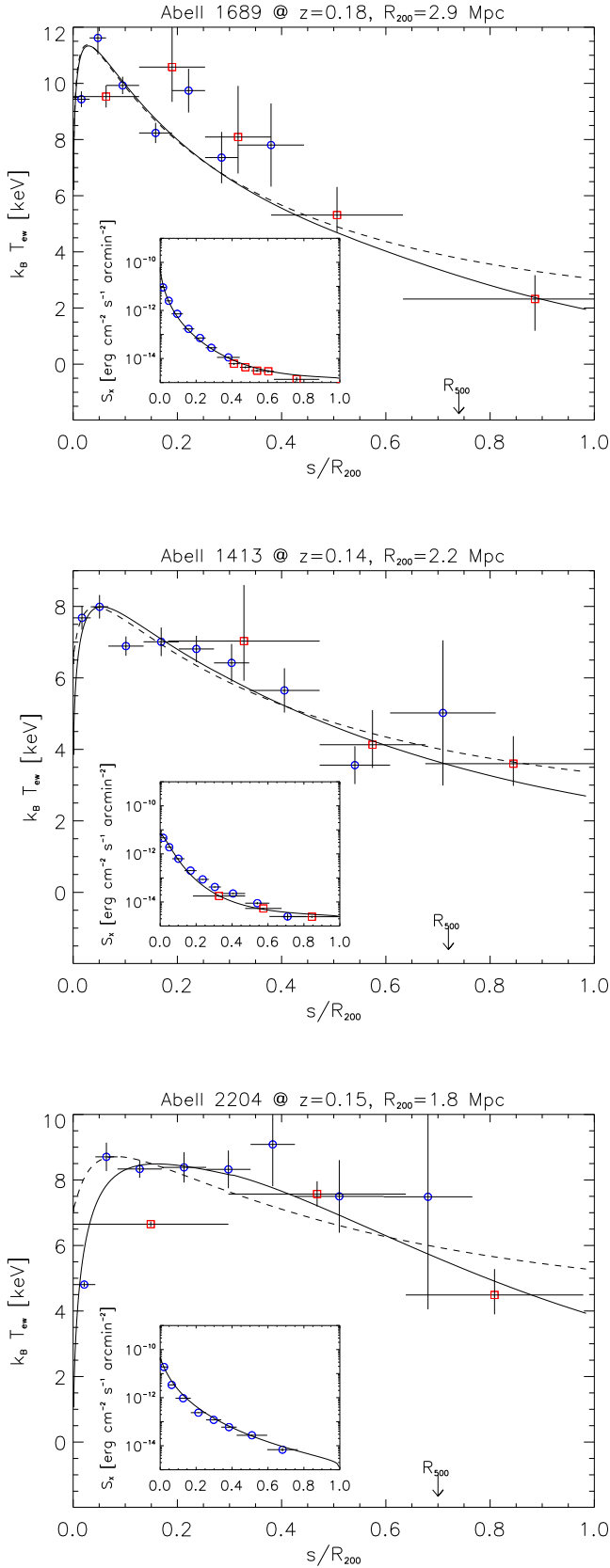
To sum up, under the *lower* accretion rates prevailing at *later* times in average environs, we expect the entropy run to *flatten* out or even *decline* into the cluster outskirts; then the temperature will decline as  $k_B T(r) = k n^{2/3} \propto r^{-2}$  or steeper, after Eq. (7) of CLFF09. Do such behaviors show up in real clusters?

### 3. A case study on current data

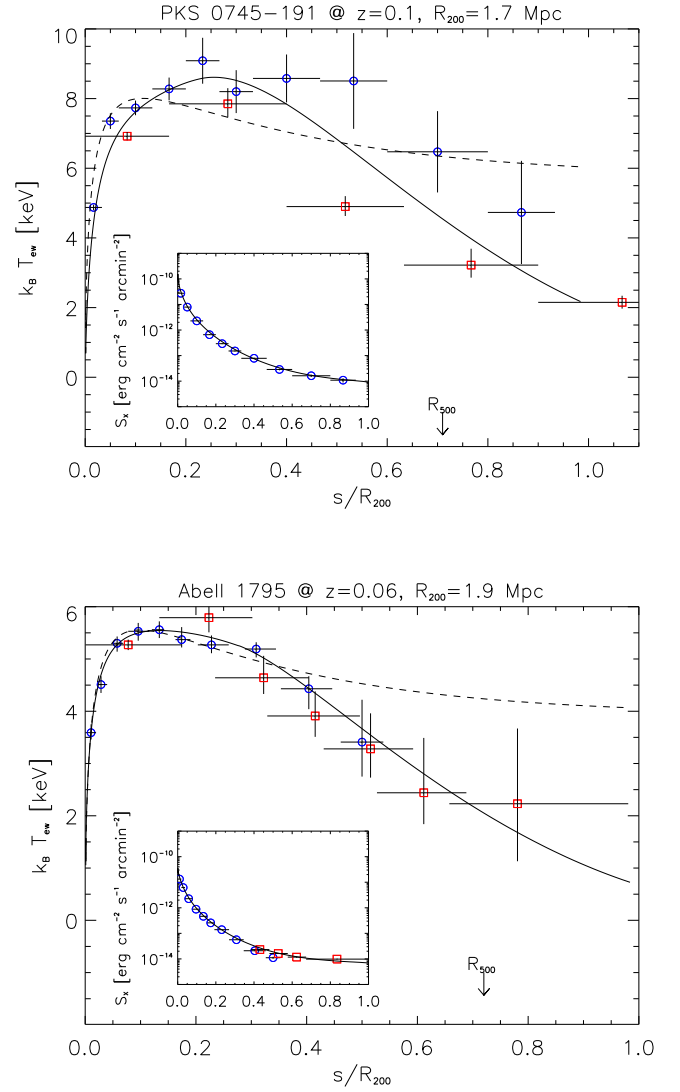
Toward an answer, we use the SM to provide profiles of density and temperature from expressing the expected entropy run in a simple form: the initial slope  $a$  still applies in the cluster body for  $r \leq r_b$ ; but for  $r > r_b$  it goes over to a decline toward the current boundary value  $a_R < a$  following  $a - a'(r/r_b - 1)$  with a constant gradient  $a'$ . So the entropy profile reads

$$k(r) = \begin{cases} k_c + (k_b - k_c) (r/r_b)^a & r \leq r_b \\ k_R (r/R)^{a+a'} e^{a'(R-r)/r_b} & r > r_b \end{cases}. \quad (4)$$

<sup>2</sup> Note that  $d \rightarrow 0$  would occur if the Dark Energy density increased with time to cause an ultimate Cosmic Doomsday (see Caldwell et al. 2003); this would imply truly vanishing accretion rates, and result into a cutoff of the temperature profiles.



**Fig. 2.** Profiles of projected X-ray temperature (brightness in the insets) for the CC clusters A1689 (top), A1413 (middle) and A2204 (bottom). Data are from Snowden et al. (2008) with *XMM-Newton* (blue circles) and from Kawaharada et al. (2010), Hoshino et al. (2010), and Reiprich et al. (2009) with *Suzaku* (red squares). Our best-fits with the SM after Eq. (4) are illustrated by the solid lines, while dashed lines refer to the fits based on Eq. (1).



**Fig. 3.** Same as Fig. 2 for the low- $z$  clusters PKS0745-191 (top) and A1795 (bottom). Data are from Snowden et al. (2008) with *XMM-Newton* (blue circles) and from George et al. (2009) and Bautz et al. (2009) with *Suzaku* (red squares).

**Table 1.** Fitting parameters from ICP temperature profiles

Cluster	$c^*$	$a$	$r_b/R$	$a'$	$\chi^2_{**}$
A1795	$8.5^{+1.9}_{-1.9}$	$1.2^{+0.3}_{-0.3}$	$0.28^{+0.02}_{-0.02}$	$1.8^{+1.3}_{-1.3}$	0.3 (2.6)
PKS0745-191	$7.6^{+1.7}_{-1.7}$	$1.9^{+1.3}_{-1.3}$	$0.23^{+0.03}_{-0.03}$	$1.1^{+0.7}_{-0.7}$	1.4 (4.4)
A2204	$5.5^{+1.1}_{-1.1}$	$1.5^{+1.1}_{-1.1}$	$0.31^{+0.07}_{-0.07}$	$0.6^{+0.4}_{-0.4}$	1.1 (2.1)
A1413	$8.3^{+1.7}_{-1.7}$	$0.9^{+0.3}_{-0.3}$	$0.27^{+0.07}_{-0.07}$	$0.2^{+0.03}_{-0.03}$	1.2 (1.9)
A1689 <sup>†</sup>	$12.4^{+5.3}_{-5.3}$	$0.7^{+0.3}_{-0.3}$	$0.5^{+0.1}_{-0.1}$	$1.6^{+1.2}_{-1.2}$	1.5 (1.7)

\* DM concentration estimated from X rays.

\*\* Reduced  $\chi^2$  values for fits with the entropy run in Eq. (4); in parenthesis the values with  $a' = 0$ , corresponding to Eq. (1).

<sup>†</sup> CC classification is controversial (see Riemer-Sørensen et al. 2009).

The outer branch describes a linear decline of the slope with the gradient  $a' \equiv (a - a_R)/(R/r_b - 1)$ ; normalizations have been set as to obtain for  $k(r)$  a continuous function and derivative. We illustrate in Fig. 1 examples of entropy profiles after Eqs. (1) and (4), with parameters indicated by the analyses below.

Adding to the several CCs and NCCs previously analyzed out to  $R/2$  in terms of the standard entropy run (see CLFF09 and Fusco-Femiano et al. 2009), here we focus on five CCs with data now available out to  $r \approx R$ , and analyze them in terms of the entropy run of Eq. (4). We report in Table 1 the resulting parameters with 68%-level uncertainties. For these old CC clusters we take  $k_c \approx 10 \text{ keV cm}^2$  as anticipated in § 2.

#### 4. Discussion and conclusions

These data clearly bear out our expectations of steep runs for  $T(r)$ , stemming from outer entropy production being reduced as the accretion rates  $\dot{M}$  of DM and intergalactic gas peter out (see § 2). We trace back such a behavior to two concurring sources: (i) the cosmological slowdown in the growth of outskirts developing at late cosmic times; (ii) shallow perturbation wings scantily feeding the outskirts growth in average or poor environs.

Under such conditions, we show that on average the entropy profiles are to *flatten* out or even *decline* into the cluster outskirts as represented by Eq. (4). Then our Supermodel yields *steep* outer profiles of projected temperatures (and flatter densities), in close agreement with current data out to  $R$ .

We also expect the cosmological decrease of the accretion rates to be locally offset in rich environs *biased* high, or in cluster sectors adjacent to filamentary large-scale structures; more standard runs of temperature are predicted there. These loom out in a sector of A1689 as observed by Kawaharada et al. (2010).

Compared with numerical simulations like the ones by Nagai et al. (2007) and Roncarelli et al. (2006), our temperature declines and entropy dearths are comparable as for clusters like A2204 and A1413; but they are quite sharper for low  $z$  clusters like A1795 and PKS0745-191, well beyond possible contaminations due to *Suzaku* PSF smearing (see Reiprich et al. 2009). Low-noise, high-resolution simulations addressing the issue of entropy production related to richness of surrounding environment or adjoining filamentary structures will be most fruitful.

We have checked that with the SM the gas mass  $m(< r)$  grows monotonically outwards, and actually faster than the DM's, so as to produce an increasing baryonic fraction by a factor 10 from  $R/20$  to  $R$  (cf. Zhang et al. 2010). So sharply declining  $T(r)$  and increasing masses are in fact consistent with thermal HE. Note that as  $\dot{M}$  decreases to the point that the infall velocities decrease to transonic values, the shocks weaken, thermalization becomes inefficient (see CLFF09), the entropy production is terminated, and thermal pressure alone cannot support HE any longer.

Equilibrium in the outskirts can be helped by bulk or turbulent, merger-induced motions; these contribute up to 10 – 20% of the total support in relaxed clusters, as gauged in terms of pressure and X-ray masses both observationally (Mahdavi et al. 2008; Zhang et al. 2010, adding to the refs. in § 3) and numerically (Nagai et al. 2007; Piffaretti & Valdarnini 2008; Bode et al. 2009; Lau et al. 2010; Meneghetti et al. 2010). A similar accuracy is intended for our predictions based on thermal HE, while a finer approximation with non-thermal contributions included in the SM will be provided elsewhere.

On the other hand, even extended HE constitutes just a useful approximation, due to fail even in relaxed clusters: locally, when minor lumps of cold gas fall into the cluster from an adjacent

filament, along with smooth accretion; globally, beyond  $R$  where the DM equilibrium is in jeopardy.

In sum, from the SM with thermal HE and optimal energy conversion in strong shocks, we find temperature profiles declining *sharply* outwards. These stem from progressive *exhaustion* of mass inflow, especially for clusters in average or poor environments at *low*  $z_{\text{obs}}$ ; such a predicted trend is consistent with the current evidence for the handful of clusters in Figs. 2 and 3.

Our punchline is that cosmology - besides affecting the cluster statistics like mass or temperature distributions (see Vikhlinin et al. 2009) - concurs with the perturbation shape to set the outer structure of *individual* clusters and their development.

All these rich phenomena expected at the *interface* between the ICP and the intergalactic medium call for extensive probing even at  $z \gtrsim 0.2$  with the next generation of X-ray telescopes planned to detect at high resolutions low-surface brightness plasma (see Giacconi et al. 2009), like *WFXT* (see <http://wfxt.pha.jhu.edu/>) and eventually *IXO* (see <http://ixo.gsfc.nasa.gov/>).

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